Development of a Novel Gas Pressurized Stripping (GPS)-Based Technology for CO_2 Capture from Post-Combustion Flue Gases
DE-FE0007567

Project Kick-Off Meeting

Carbon Capture Scientific, LLC.
CONSOL Energy Inc.
Nexant Inc.

Pittsburgh, PA November 8, 2011

Presentation Outline

- ❑ **Project Overview**
- ❑ **Technology Fundamentals and Background**
- ❑ **Scope of Work**
- ❑ **Technical Approach**
- ❑ **Project Management**

Project Objectives

- Perform bench-scale tests of individual process units to obtain necessary process design data for the pilot scale
- Conduct computer simulations to maximize the benefit of the GPS technology for existing power plants
- Carry out experimental investigation of selected solvents to minimize the economic risk of the GPS technology.

Project Team and Focus

DOE/NETL

- COR- Timothy Fout

Carbon Capture Scientific, LLC

- Computer simulation to optimize GPS based process for existing power plants
- Bench-scale experiments to obtain process design data for GPS based process

CONSOL Energy Inc.

- Work with CCS to acquire phase equilibrium and related process design data

Nexant Inc.

- Conduct techno-economic analyses for the GPS based technology

Project Team- Key Personnel

- **NETL Timothy E. Fout (COR)**

- **CCS**

	Shiaoguo (Scott) Chen	(PI)
	Zijiang (John) Pan	(Co-PI)
	Kevin C. O'Brien	(Project manager)
	Zhiwei (David) Li	(Task leader)
	Technician A	(Laboratory specialist)

- **CONSOL Energy Inc.**

	Daniel P. Connell	(Co-PI)
	Mark Dunkerley	(Co-PI)
	Richard Winchel	(Technical advisor)

- **Nexant Inc.**

	Gerald Choi	(PI)
	Robert Chu	(Sr. Chemical Engineer)

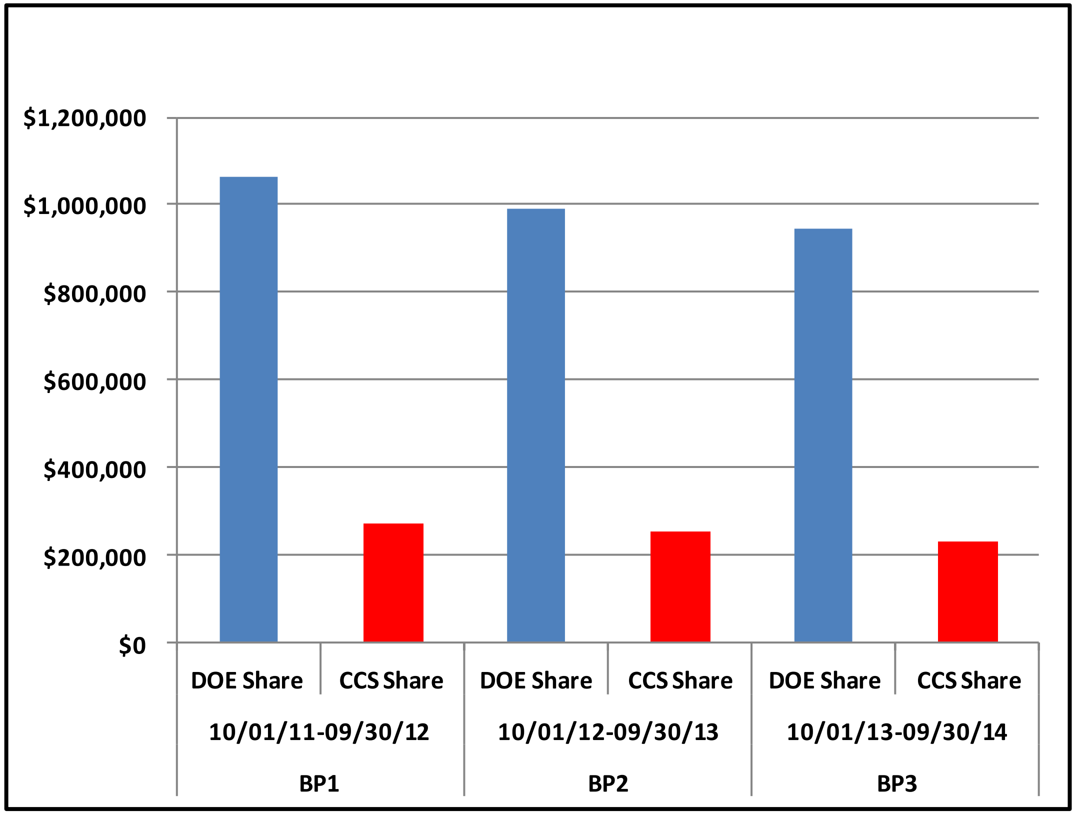
Project Budget

Project duration: 10/1/2011 – 9/30/2014

	Budget, $
DOE	2,999,756
CCS	751,178*
Total	3,750,934

*including $84,605 from CONSOL Energy

(Cost share is ~20%)



DOE funding and cost share on a yearly basis

Presentation Outline

- Project Overview
- **Technology Fundamentals and Background**
- Scope of Work
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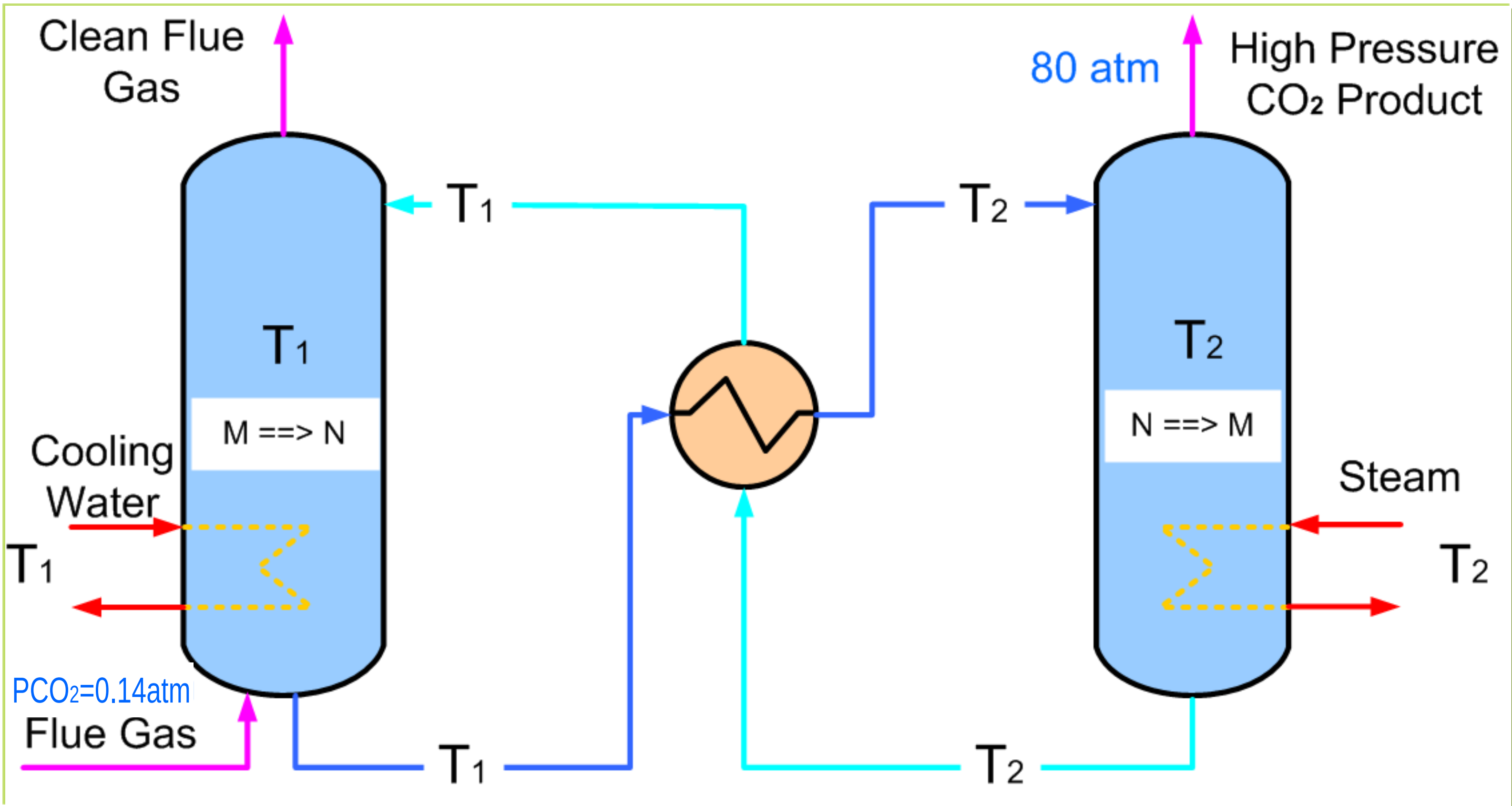
Thermodynamics of the Post-Combustion CO_2 Capture Processes

- A generic CO_2 capture/regeneration process
- Minimum heat requirement of the generic process
- Electricity equivalent of the minimum heat
- Limitations of amine as absorption/stripping solvents
- Repeated generic CO_2 capture processes
- Thermodynamics of repeated generic processes

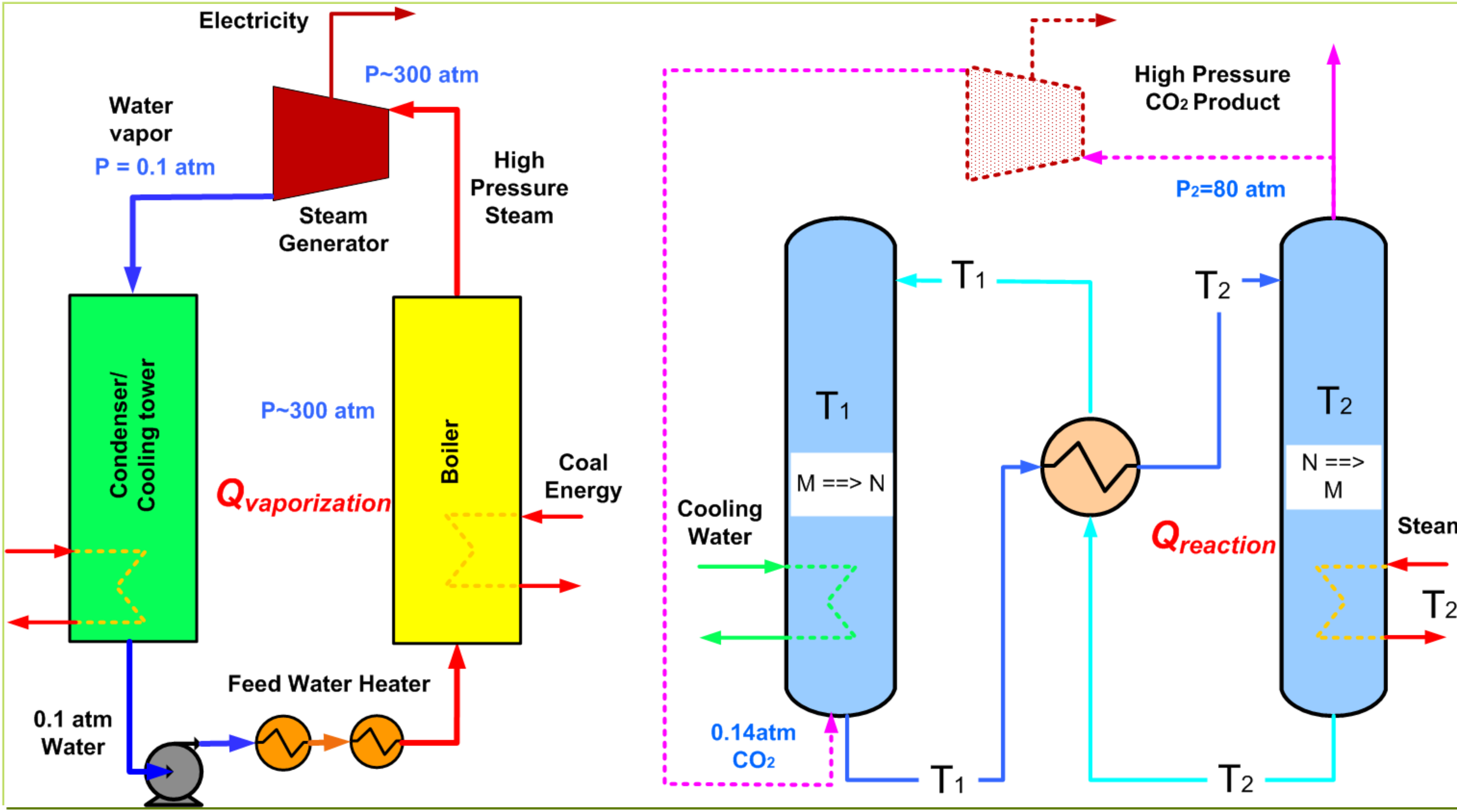
A Generic Process for CO_2 Capture from Post-Combustion Flue Gases

$$M + CO_2 \longleftrightarrow N + \Delta H$$



Ignore all the driving force for heat transfer

Analogy between Power Generation and CO_2 Capture from Flue Gas



Capture /Regeneration Operating Parameters

Heat of Reaction	$= \Delta H$ (kJ/kgCO_2)
CO_2 Capture temperature	$= T_1 = 313$ (K)
Regeneration temperature	$= T_2 = ?$ (K)
CO_2 partial pressure at capture	$= P_1 = 0.14$ (atm.)
CO_2 partial pressure at regeneration	$= P_2 = 80$ (atm.)
CO_2 recovery rate	= 90%

Minimum Heat Requirement of the Generic CO_2 Capture Process

CO_2 Capture/ Regeneration:

$$M + CO_2 \Leftrightarrow N + \Delta H$$

Equilibrium constant expression:

$$solid: \quad K = \frac{1}{P_{CO2}}$$

$$Ideal\ solution: \quad K = \left(\frac{x_N}{x_M}\right)\frac{1}{P_{CO2}}$$

$$Non\ ideal\ liquid: \quad K = \left(\frac{\gamma_N x_N}{\gamma_M x_M}\right)\frac{1}{P_{CO2}}$$

And the equation correlates K and T *is so called Van't Hoff equation*:

$$\frac{d \ln K}{dT} = \frac{\Delta H}{RT^2}$$

Minimum Heat Requirement of the Generic CO_2 Capture Process

For non ideal liquid solvents:

$$\frac{d\ln K}{dT} = \frac{\partial \ln \gamma_N + \partial \ln x_N - \partial \ln \gamma_M - \partial \ln x_M - \partial \ln P_{CO2}}{\partial T}$$

$$= \frac{\partial \ln \gamma_N - \partial \ln \gamma_M - \partial \ln P_{CO2}}{\partial T} \approx -\frac{\partial \ln P_{CO2}}{\partial T} = -\frac{\Delta H}{RT^2}$$

The relationship between activity coefficient and temperature is:

$$\frac{d\,ln\gamma_i}{dT} = -\frac{\Delta \overline{H}_i}{RT^2}$$

ΔH_i is partial molar heat of mixing for component i, usually it is much smaller than heat of reaction

Minimum Heat Requirement of the Generic CO_2 Capture Process

Ignore activity coefficient change with temperature, above equation can be integrated:

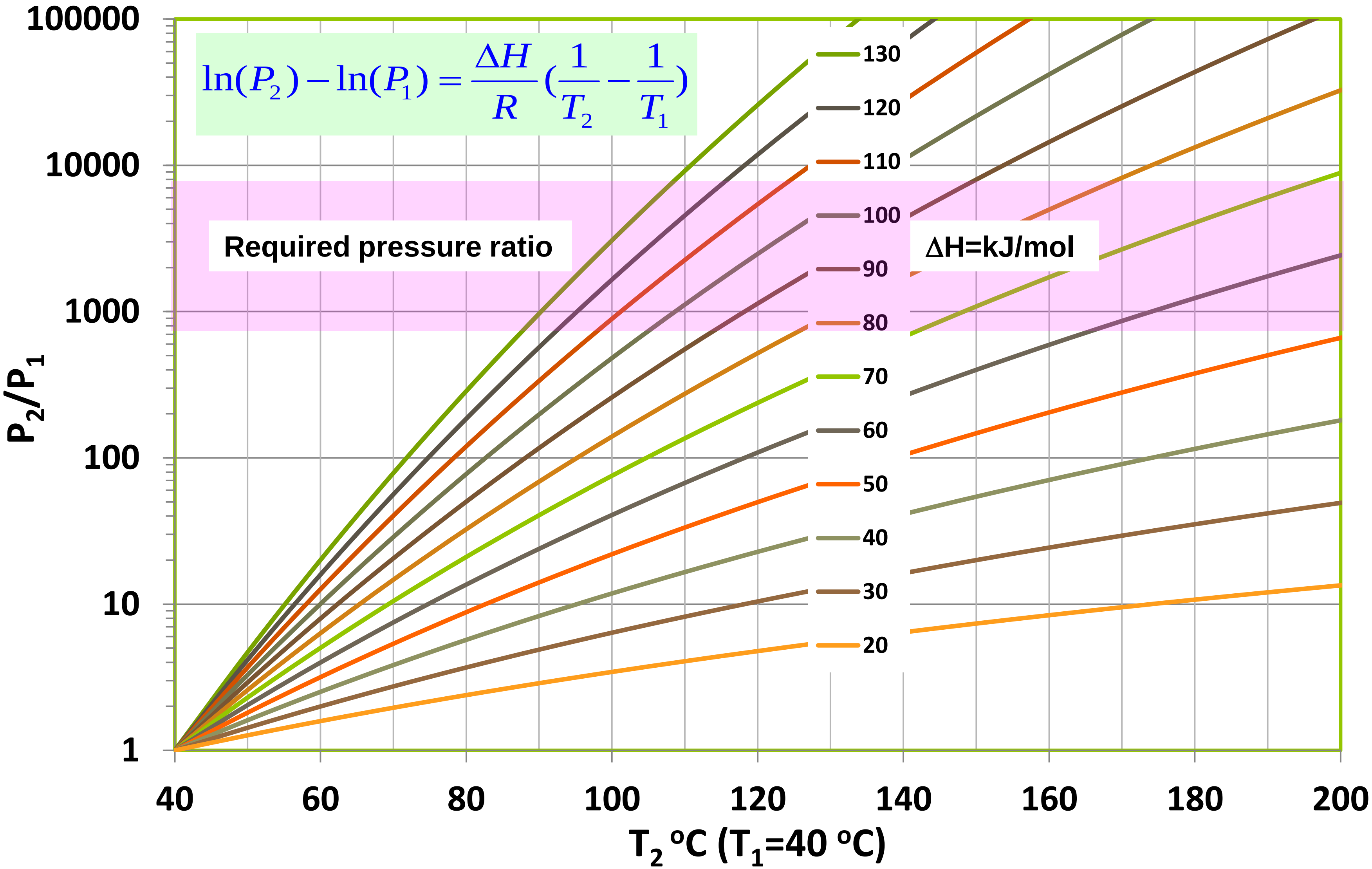
$$\ln(P_2) - \ln(P_1) = \frac{\Delta H}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

And rearrange above, we have:

$$\Delta H = -R[\ln(P_2) - \ln(P_1)]\frac{T_1 T_2}{T_2 - T_1}$$

Minimum heat requirement can be calculated for different temperature swing ranges and different pressure requirement

Minimum Heat Requirement



Electricity Equivalent of the Minimum Heat

Minimum heat:

$$\Delta H = -R[\ln(P_2) - \ln(P_1)]\frac{T_1T_2}{T_2 - T_1}$$

And the Carnot Efficiency of the ΔH at T_2 is:

$$\eta_{carnot} = (1 - T_1/T_2)$$

Thus the electricity equivalent is:

$$W = (\Delta H) * \eta_{carnot} = R[\ln(P_2) - \ln(P_1)]\frac{T_1T_2}{T_2 - T_1} \times (1 - T_1/T_2)$$

$$= RT_1(\ln(P_2) - \ln(P_1)) = RT_1 \ln(P_2 / P_1)$$

$$\textbf{\textit{Idel gas}}: \quad \boldsymbol{W_{comp}} = -\int_{v_1}^{v_2} P\, dv = -\int_{v_1}^{v_2} \frac{R\boldsymbol{T}_1}{v}\, dv = R\boldsymbol{T}_1 ln\frac{P_2}{P_1}$$

Electricity Equivalent of the Minimum Heat --Case of Post-Combustion with 90% Removal

Post-Combustion CO_2 capture with 90% removal:

P_1= 0.014~0.14atm (90% of CO_2 removal)

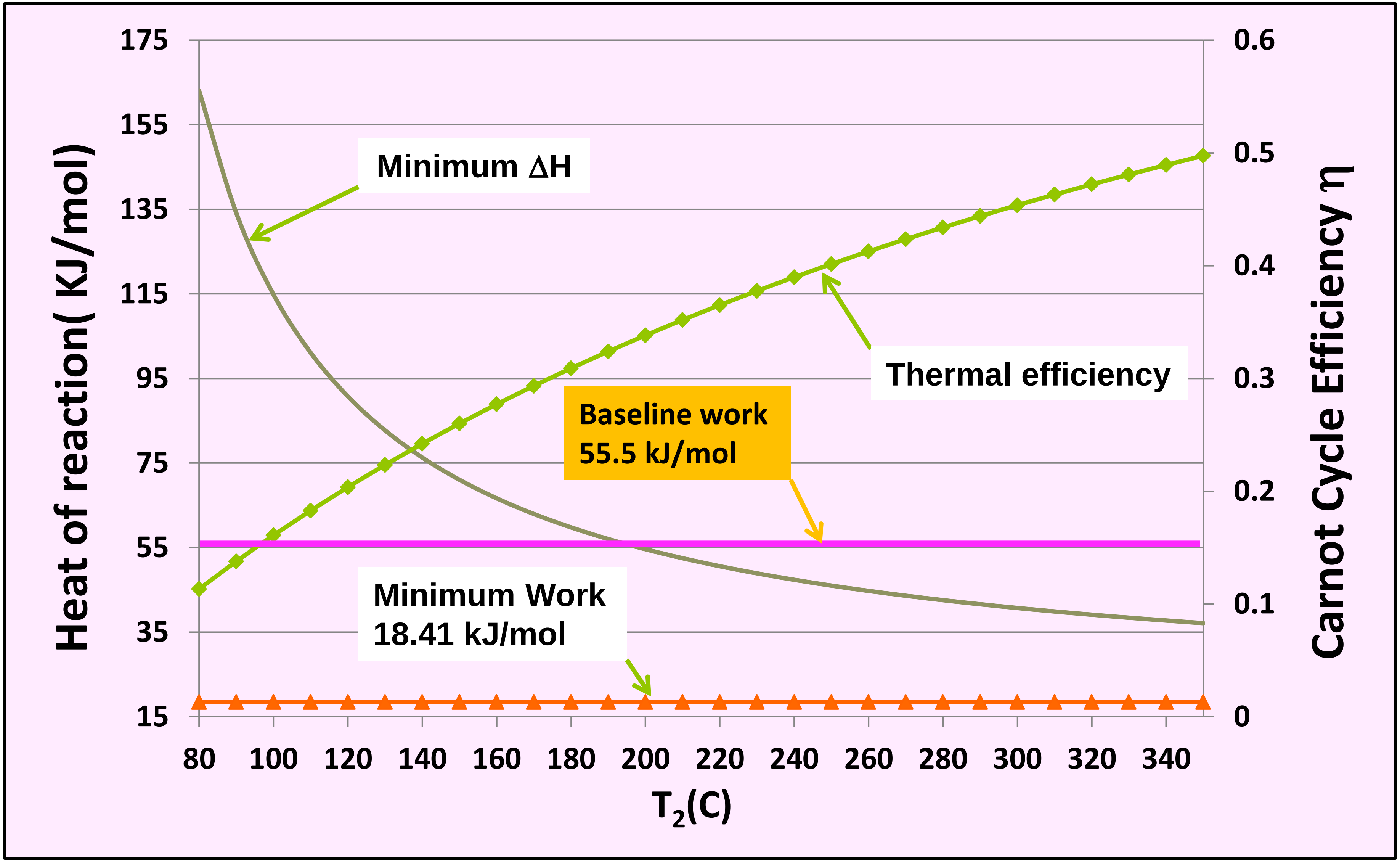
P_2=80 atm

$$W = (\Delta H) * \eta_{carnot} = RT_1[\ln(P_2) - \ln(P_1)]$$

At 90% removal P_1 changes from P_a=0.014 to P_b=0.14 atm and the average minimum work is:

$$W = RT_1(\ln P_2 - P_b \ln P_b + P_a \ln P_a + (P_b - P_a))/(P_b - P_a))$$
$$= 18.41(kJ/mol) = 0.116\,(kWh/kgCO_2)$$

Minimum Heat, Thermal Efficiency and Minimum Work



Limitations of Amine As Absorption/Stripping Solvent

CO_2 conditions for post combustion flue gas:

Initial P: P_1= 0.014~0.14atm (90% of CO_2 removal)

Product P: P_2=80 atm

Absorption T: T_1=313K

Stripping T: T_2=393K

Required heat of reaction:

$$\Delta H = -R[\ln(P_2) - \ln(P_1)]\frac{T_1 T_2}{T_2 - T_1}$$

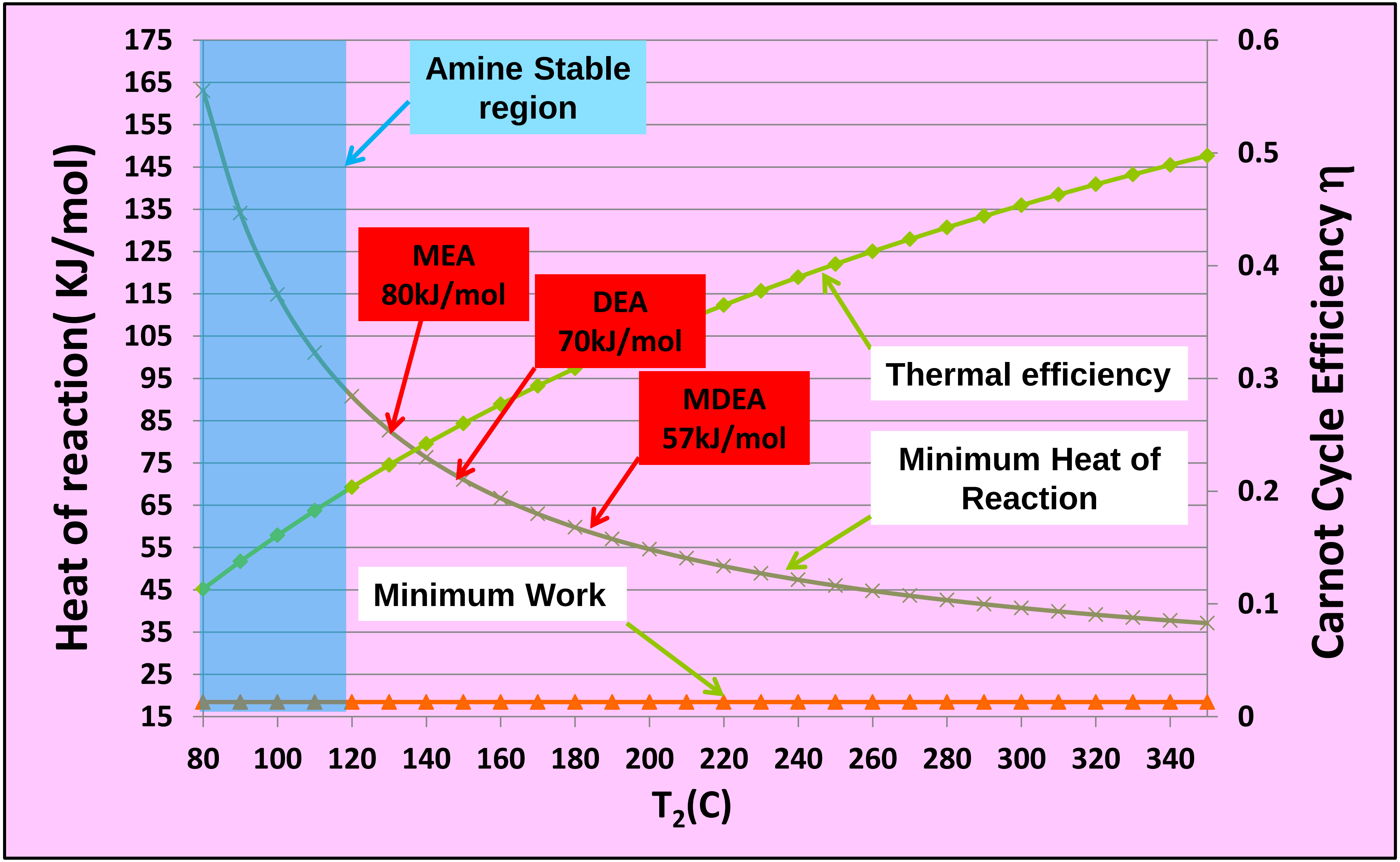
$$= 12.571 \times [\ln(80) - \ln(P_1)] = 55.88 - 12.571 \ln(P_1)$$

P_1 changes from P_a=0.014 atm to P_b=0.14 atm; by integrating above equation between P_a and P_b, we have:

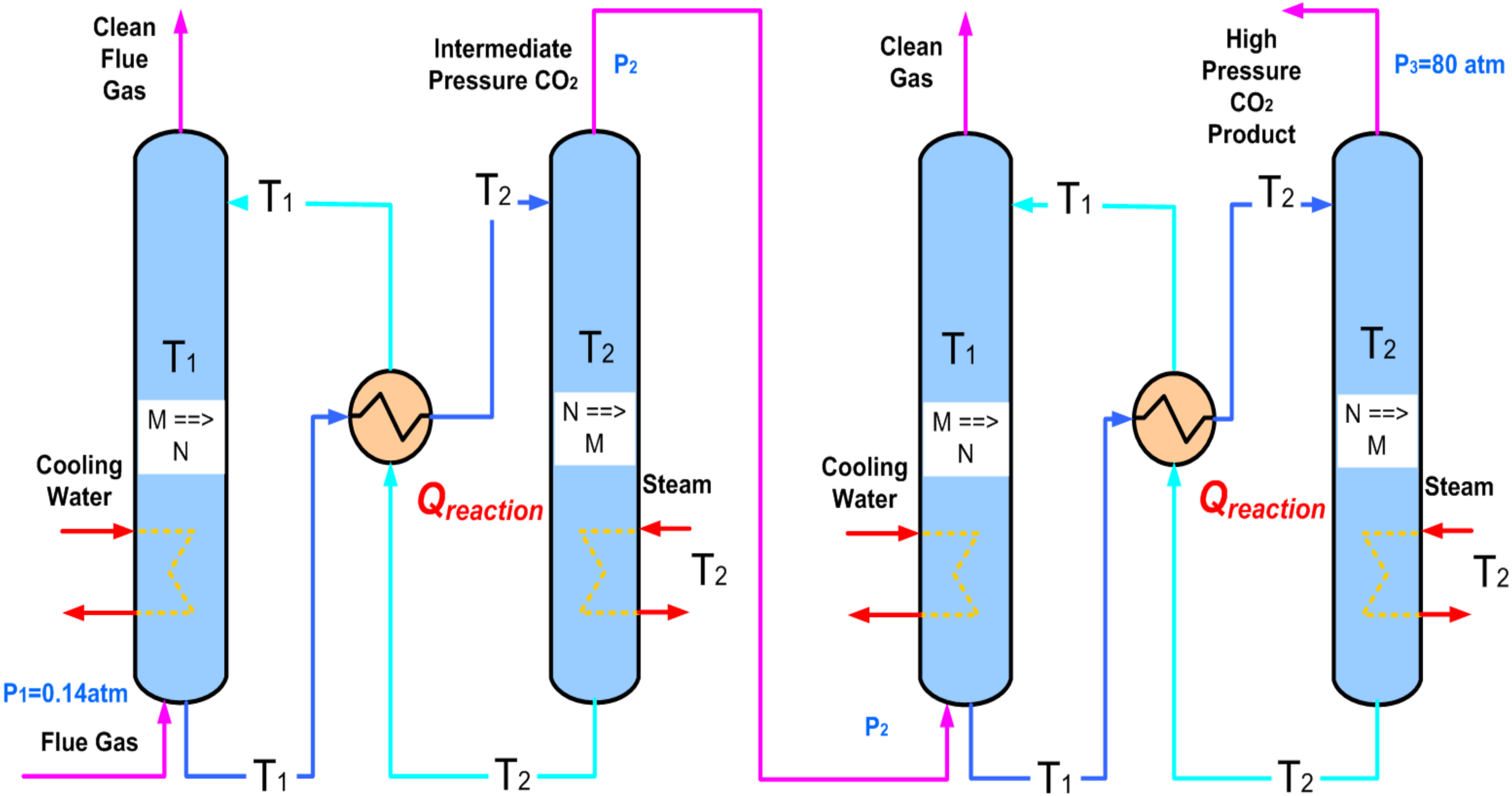
$$\Delta H = 55.88 - 12.571(P_b \ln(P_b) - P_a \ln(P_a) - (P_b - P_a)) / (P_b - P_a)$$

$$= 90.44(kJ/molCO_2) = 2055(kJ/kgCO_2)$$

Limitations of Amine As Absorption/Stripping Solvent



Repeated CO_2 Absorption/Stripping Process



Thermodynamics of the Repeated Generic Process

Repeated absorption/stripping cycles between the same temperature range (e.g. 40 - 120 ^{0}C):

First cycle:

$$\ln(P_2) - \ln(P_1) = \frac{\Delta H_1}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

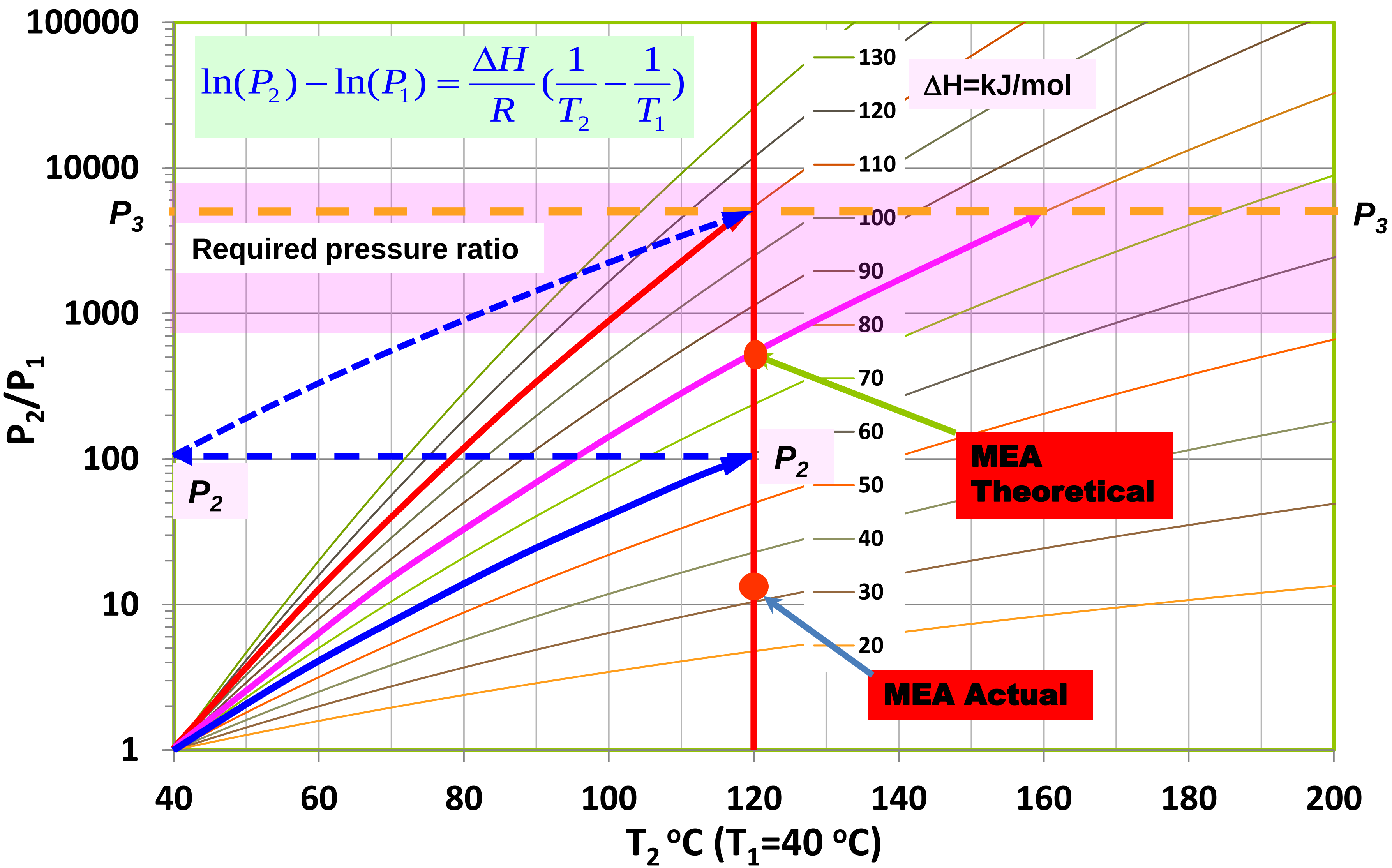
Second cycle:

$$\ln(P_3) - \ln(P_2) = \frac{\Delta H_2}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

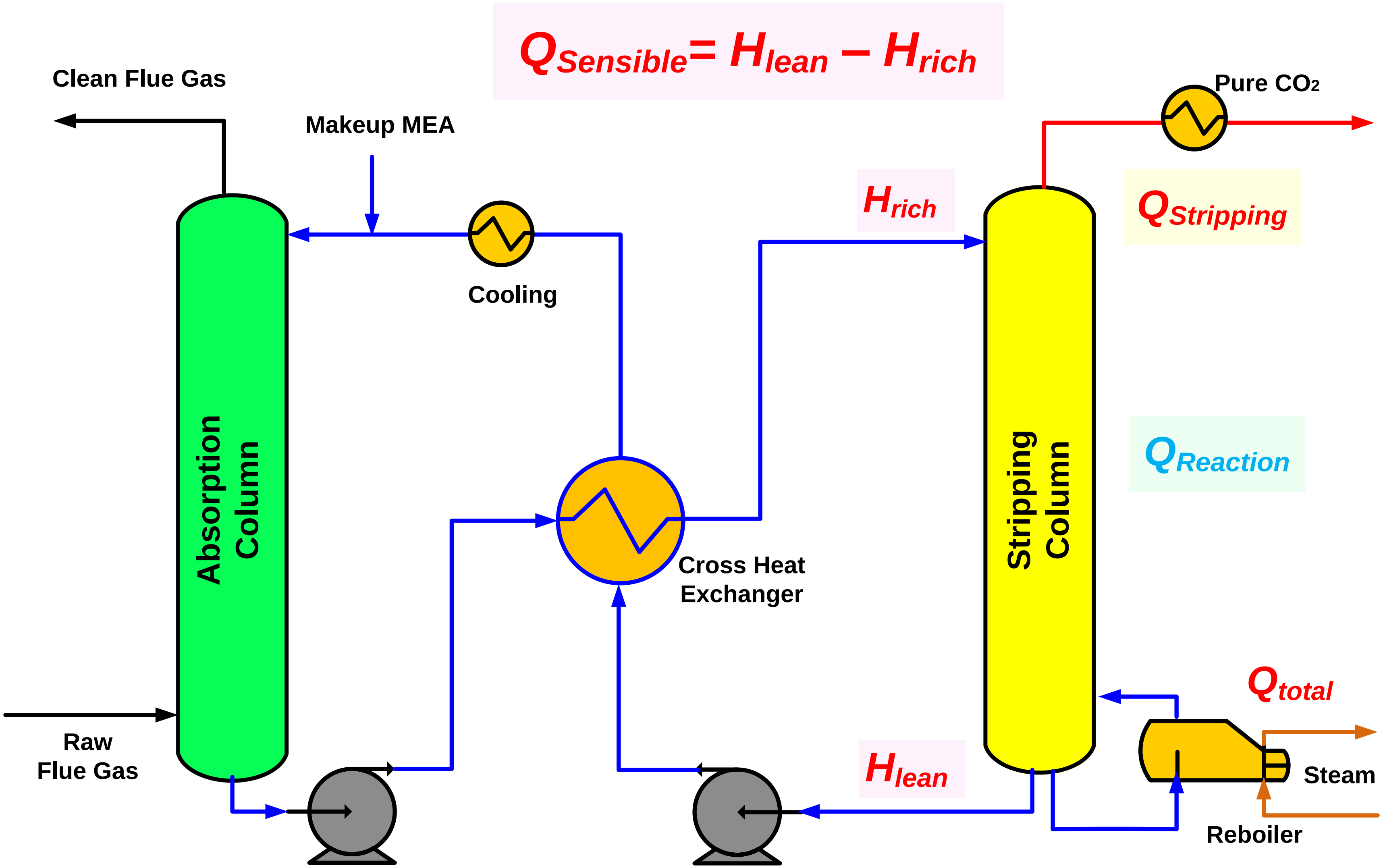
Combining the two cycles:

$$\ln(P_3) - \ln(P_1) = \frac{\Delta H_1 + \Delta H_2}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Thermodynamics of the Repeated Generic Process



Conventional Amine-Based Absorption/Stripping Processes



Heat Components of the Conventional Process

$$Q_{total} = Q_{sensible} + Q_{reaction} + Q_{stripping}$$

$$Q_{sensible} = \frac{C_p\left(T_{lean\ hot} - T_{rich\ hot}\right)}{\Delta Loading}$$

$$Q_{reaction} = \Delta H_{reaction}$$

$$Q_{stripping} = \left(\frac{P_{H_2O}}{P_{CO_2}}\right)_{\left(\begin{array}{l}\text{Top of} \\ \text{the} \\ \text{stripper}\end{array}\right)} \Delta H_{H_2O}$$

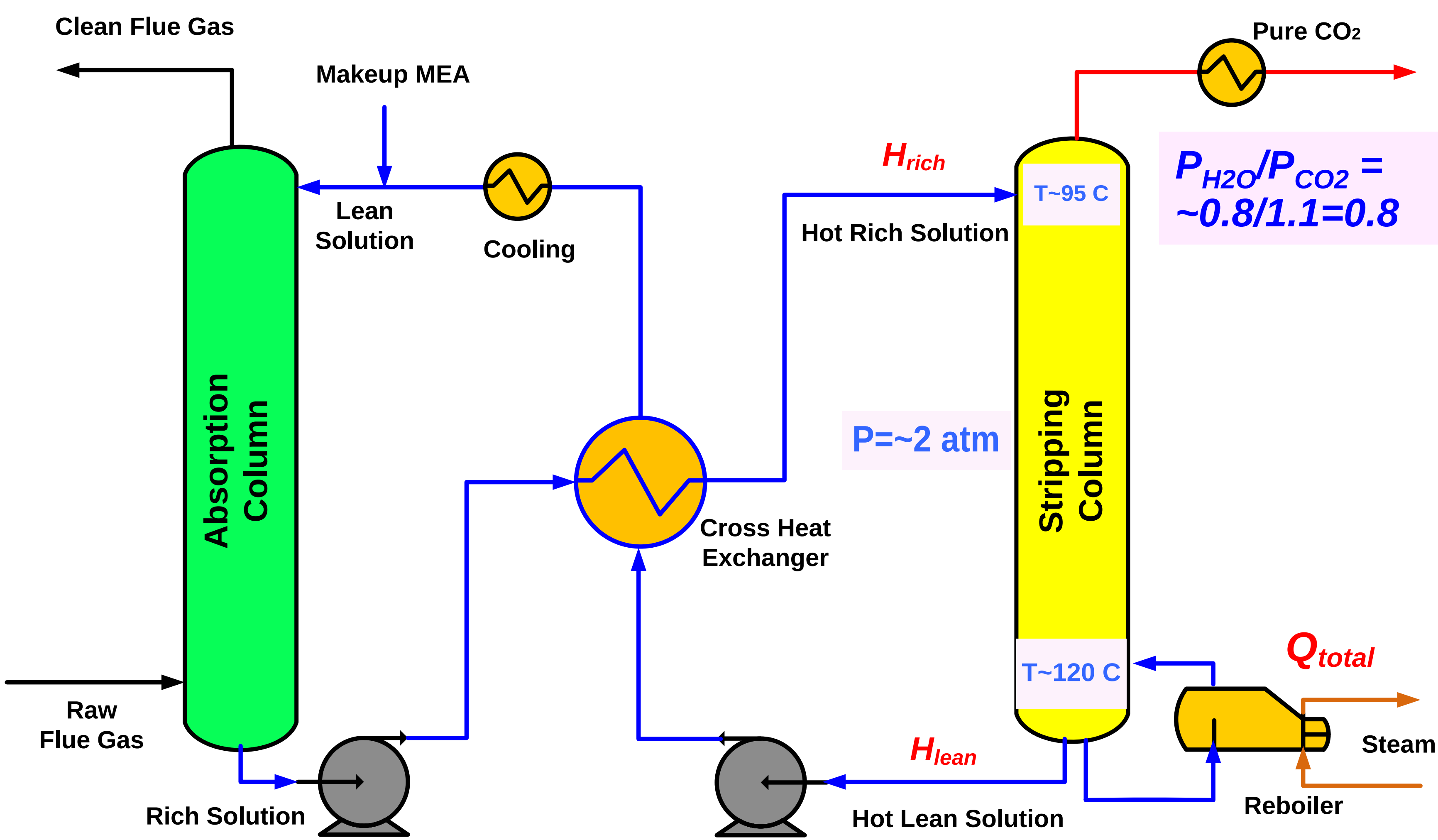
Issues with Conventional Strippers

- *Water vapor is used as stripping gas*
- *Low operating pressure*
- *Water vapor is also used as a heat carrier*

Consequences:

- *Low thermal efficiency*
- *High compression work*

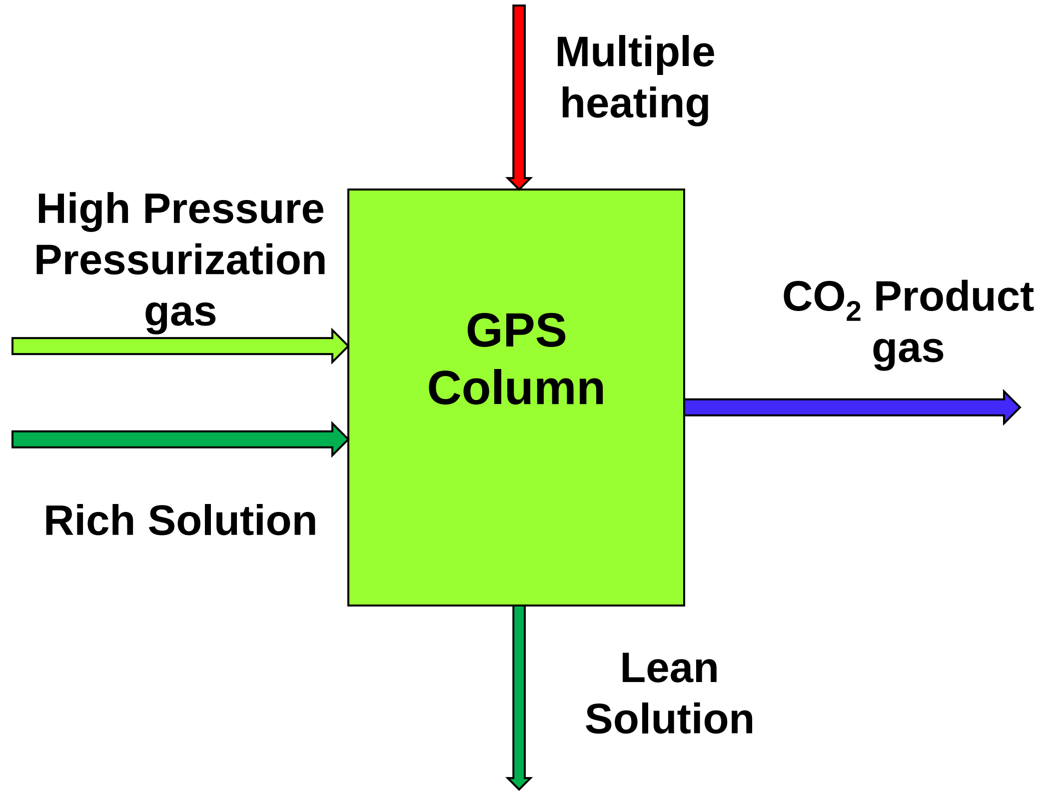
Conventional Amine-Based Absorption/Stripping Processes



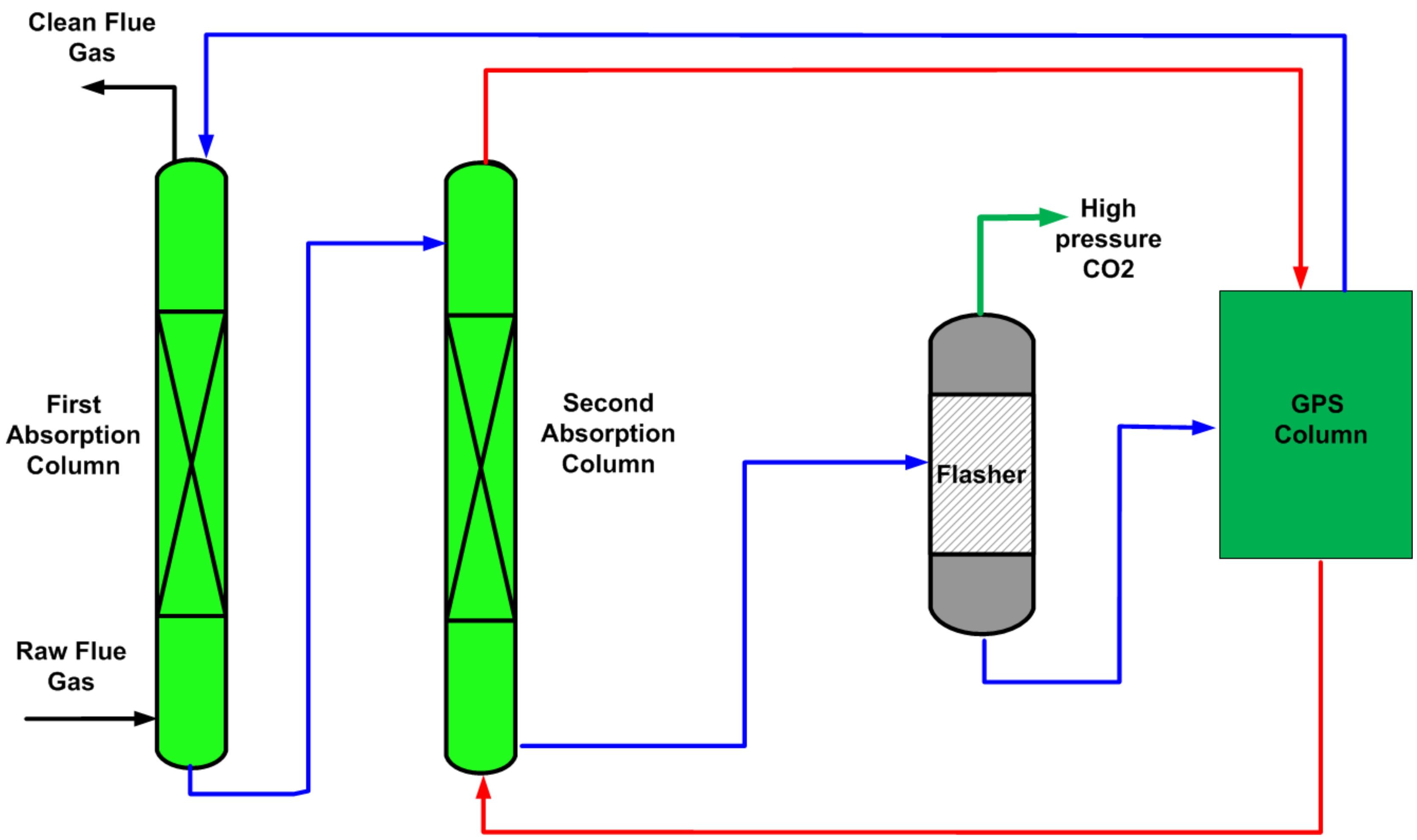
The Novel Gas Pressurized Stripping (GPS) Column

- Using a high pressure gas to create high pressure CO_2

- Introducing multiple heaters



Novel GPS Based Absorption/Stripping Process



Advantages of the GPS Based Processes

- **Uses on-the shelf technology**
  - Most suitable for large scale applications such as power plants
- **High operating pressure**
  - Low stripping heat
- **Minimal or no need for mechanical CO_2 compression**
  - Uses thermal compression
  - High thermal efficiency (low exergy loss)
- **Flexible**
  - Many common units with the conventional absorption/stripping processes
  - Can be repeatedly used depending on the needs
- **Second absorption step can reduce oxidative degradation**
  - Second absorber is a stripper for absorbed oxygen

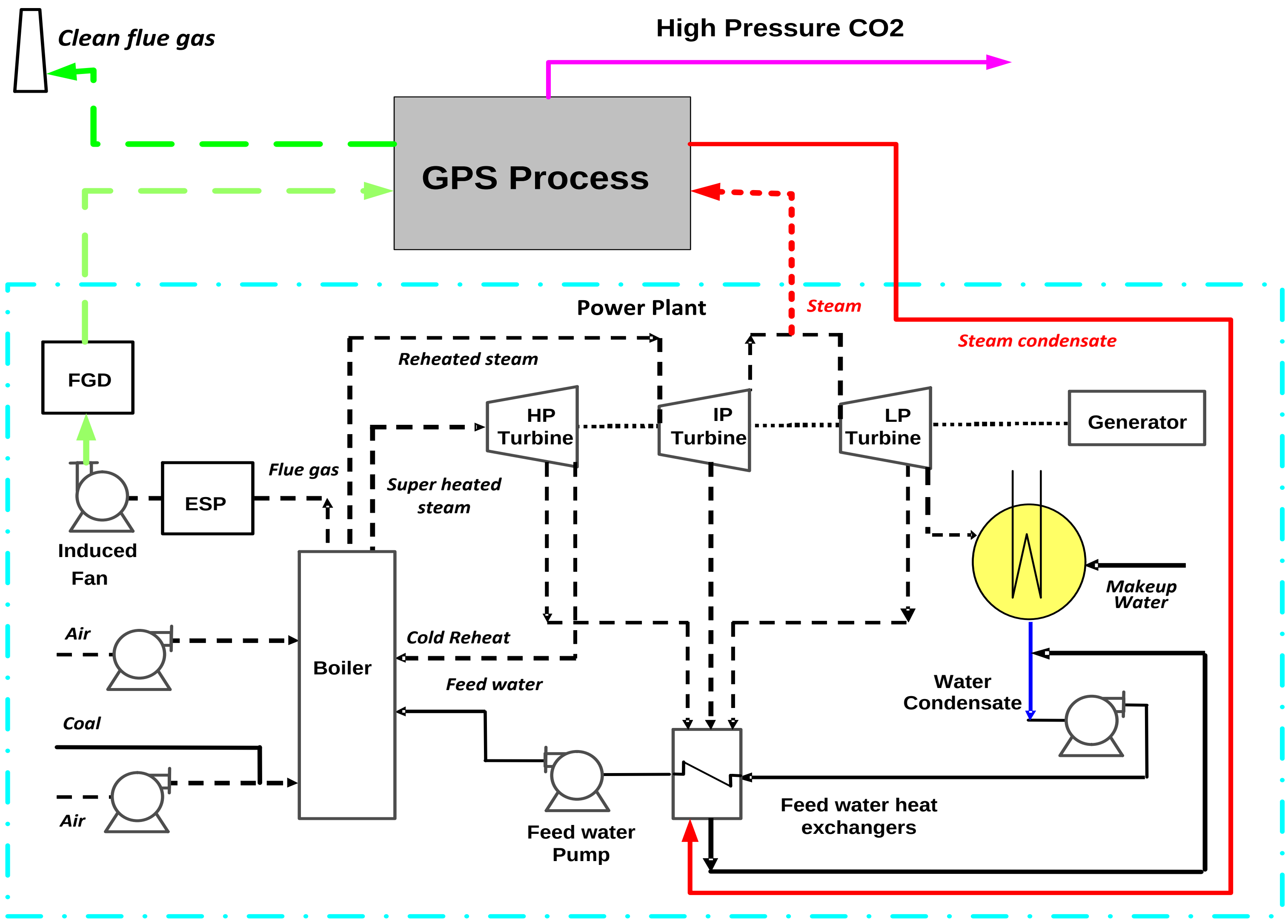
Comparison of Heat Usage for Conventional and GPS Processes

	Conventional Process	GPS Process
$Q_{sensible}$	$\dfrac{C_p(T_{lean\,hot}-T_{rich\,hot})}{\Delta Loading}$	$\dfrac{C_p(T_{lean\,hot}-T_{rich\,hot})}{\Delta Loading}$
$Q_{reaction}$	ΔH_1	$\boxed{\Delta H_1+\Delta H_2}$
$Q_{stripping}$	$\left(\dfrac{P_{H_2O}}{P_{CO_2}}\right)_{\left(\substack{\text{At top}\\ \text{of the}\\ \text{stripper}}\right)}\Delta H_{H_2O}$	$\boxed{\left\{\left(\dfrac{P_{H_2O}}{P_{CO_2}}\right)_{\left(\substack{\text{Top of}\\ \text{the GPS}\\ \text{stripper}}\right)}+\left(\dfrac{P_{H_2O}}{P_{CO_2}}\right)_{\left(\substack{\text{At the}\\ \text{flashers}}\right)}\right\}\Delta H_{H_2O}}$

Preliminary Computer Simulation Results of the GPS Process

Process	Current MEA	GPS Process
First Reaction Heat $MJ/kgCO_2$	1875	2550
Second Reaction Heat $MJ/kgCO_2$	0	
Sensible Heat $MJ/kgCO_2$	1150	425
Stripping Heat $MJ/kgCO_2$	850	220
Total Heat $MJ/kgCO_2$	3875	3195
Compression Work $kWh/kgCO_2$	0.1	0.017
Electricity Equivalent $kWh/kgCO_2$	**0.30**	**0.18**

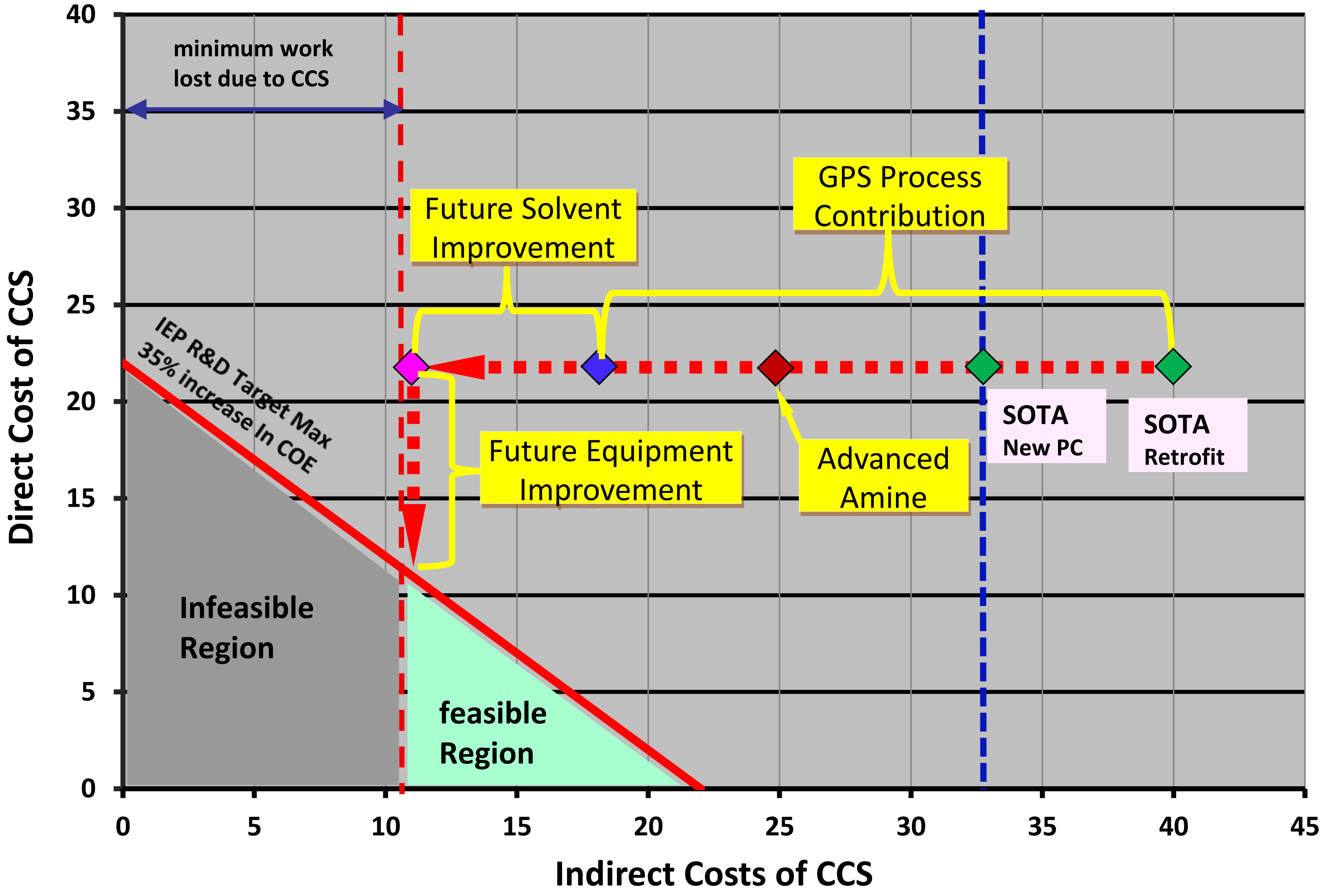
Integration of a GPS process with an existing power plant



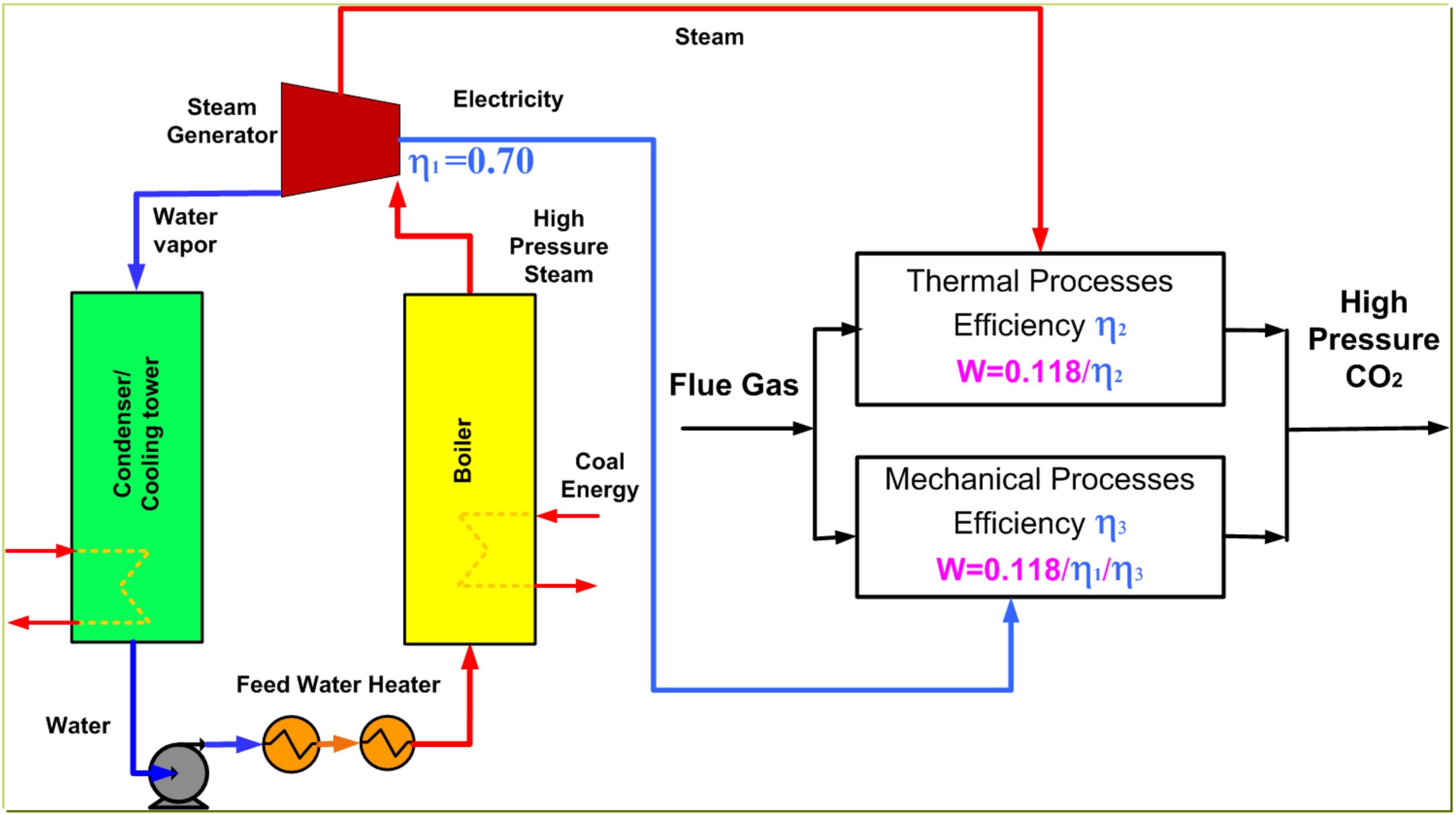
Achieving DOE's Techno-economic Goals

- **Direct Costs**: capital and operating costs associated with capture, transport, and sequestration of CO_2
- **Indirect Costs**: costs of modification of existing plant AND other costs associated with de-rating the plant
- Indirect costs dominate over direct costs

Goal Diagram for EPEC CCS *Incremental Mills/kWh*



Comparison between mechanical and thermal processes



Presentation Outline

- Project Overview
- Technology Background
- Scope of Work
- Technical Approach
- Project Management

Scope of Work

Combine experimental, modeling/process simulation, and techno-economic analysis studies to develop and evaluate the GPS technology

- Carbon Capture Scientific, LLC
  - Kinetics and thermodynamics tests using Individual process units
    - First and second absorber design
    - GPS column design
    - Flashers design
- CONSOL Energy Inc.
  - Solvent data and assistance in column design / testing
    - Phase Equilibrium data for selected solvent at high CO_2 loading and high temp
    - Heat capacity and viscosity of selected solvent
    - Column design / testing assistance
- Nexant Inc.
  - Systems analysis and preliminary techno-economic evaluation

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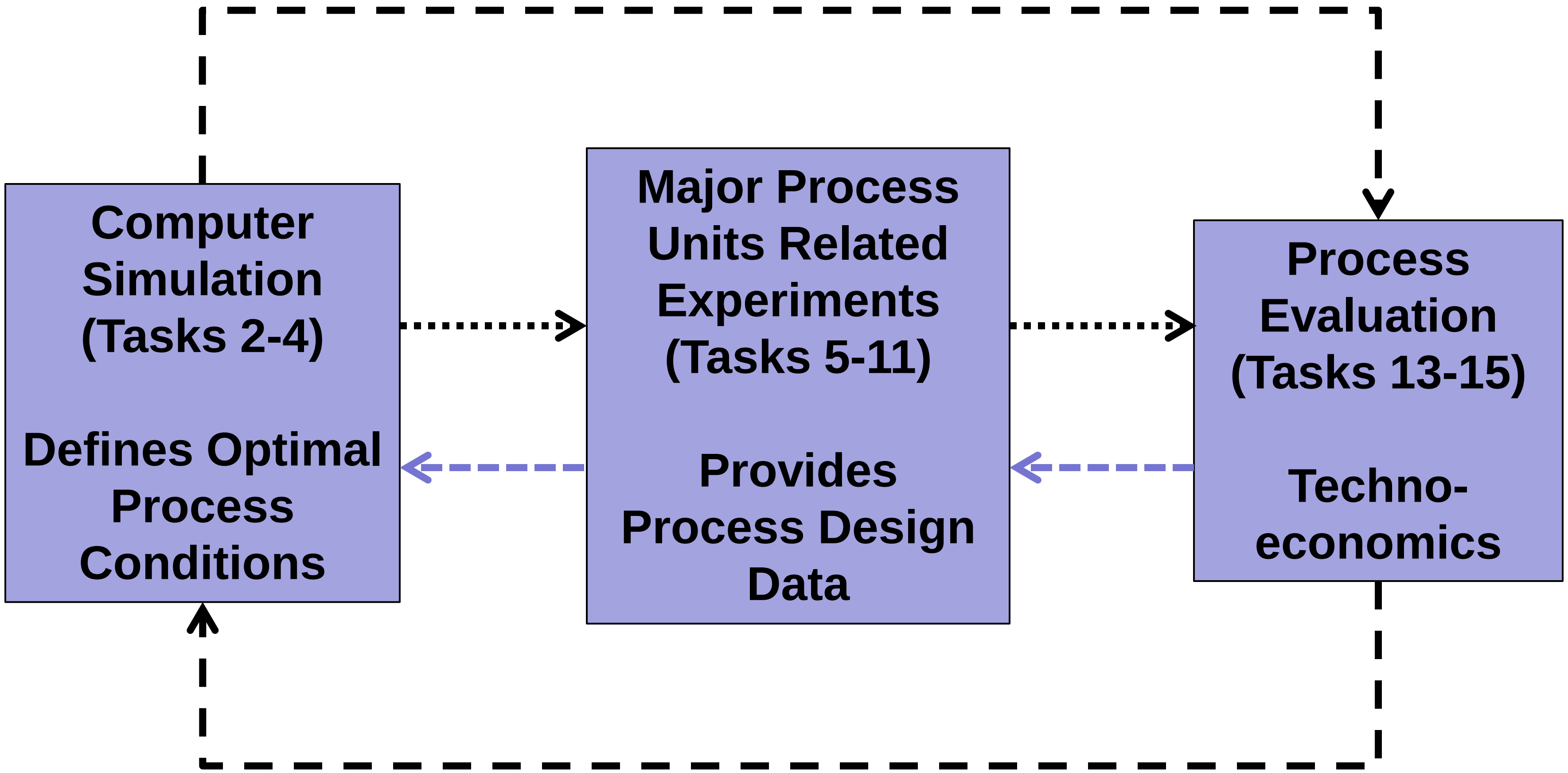
Technical Approach to Optimize & Iterate to Achieve DOE Goals



Tasks Designed to Utilize Unique Strengths of Organizations

Task	Description	Type	Focus	CCS	CONSOL	Nexant
1	Project planning & management	n/a	PM	X		
2	Optimization of GPS process	Computer Simulation	Process	X		
3	Optimization of GPS process for existing plant	Computer Simulation	Process	X		
4	Optimization of flasher operating conditions	Computer Simulation	Process	X		
5	Data measurement at high loading and high Temp	Process Related Experiments	Solvent		X	
6	First absorption column testing	Process Related Experiments	Process	X	X	
7	GPS column design/fabrication and testing	Process Related Experiments	Process	X	X	
8	Second absorption column testing	Process Related Experiments	Process	X	X	
9	Stability of solvent at high loading and Temp	Process Related Experiments	Solvent	X		
10	Corrosion test at high loading and Temp	Process Related Experiments	Solvent	X		
11	Physical properties measurement	Process Related Experiments	Solvent		X	
12	Survey of EH&S of GPS process	Process Related Experiments	Solvent	X		
13	Preliminary techno-economic analysis	Process Evaluation	Economics			X
14	Revising of techno-economic analysis	Process Evaluation	Economics			X
15	Updated techno-economic analysis	Process Evaluation	Economics			X

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Project Organization

US Dept. of Energy
Contracting Officer's Representative

CCS
Principle Investigator
Dr. Shiaoguo Chen

Steering committee

- DOE/NETL Timothy Fout
- Dr. Shiaoguo Chen (CCS)
- Dr. Kevin O'Brien (CCS)
- Mr. Richard A. Winschel (CONSOL)
- Dr. Gerald Choi (NEXANT)

Task 1. Planning Management & Reporting
CCS leads
Dr. Kevin O'Brien (CCS, 2100 hours)
Dr. Shiaoguo Chen (CCS, 760 hours)

Task 2. GPS column study and its optimization
CCS leads
Dr. Zhiwei Li (CCS, 920 hour)
Dr. Shiaoguo Chen (CCS, 104 hours)

Task 3. Optimization of GPS process for existing plant
CCS leads
Dr. Zhiwei Li (CCS, 920 hour)
Dr. Shiaoguo Chen (CCS, 112 hours)

Task 4. Optimization of flasher operating conditions
CCS leads
Dr. Zhiwei Li (CCS, 920 hour)
Dr. Shiaoguo Chen (CCS, 112 hours)

Task 5. Measurement of phase equilibrium data at high loading and high T
CONSOL leads
Mr. Daniel Connell (CONSOL, 255 hours)
Dr. Shiaoguo Chen (CCS, 300 hours)

Task 6. First absorption column testing
CCS leads
Dr. Shiaoguo Chen (CCS, 276 hours)
Dr. Zijiang Pan (CCS, 200 hour)
Mr. Dunkerley (CONSOL, 85 hour)

Task 7. GPS column design/fabrication and testing
CCS leads
Dr. Shiaoguo Chen (CCS, 368 hours)
Dr. Zijiang Pan (CCS, 380 hour)
Mr. Dunkerley (CONSOL, 408 hours)

Task 8. Second absorption column testing
CCS leads
Dr. Shiaoguo Chen (CCS, 128 hours)
Dr. Zijiang Pan (CCS, 265 hour)
Mr. Daniel Connell (CONSOL, 272 hours)

Task 9. Stability of solvent at high loading and high T
CCS leads
Dr. Shiaoguo Chen (CCS, 200 hours)
Dr. Zijiang Pan (CCS, 600 hours)

Task 10. Corrosion test at high loading and high T
CCS leads
Dr. Shiaoguo Chen (CCS, 200 hours)
Dr. Zijiang Pan (CCS, 600 hours)

Task 11. Physical properties measurement
CCS leads
Dr. Shiaoguo Chen (CCS, 200 hours)
(CCS, 600 hours)
Mr. Dunkerley CONSOL, 352 Hours

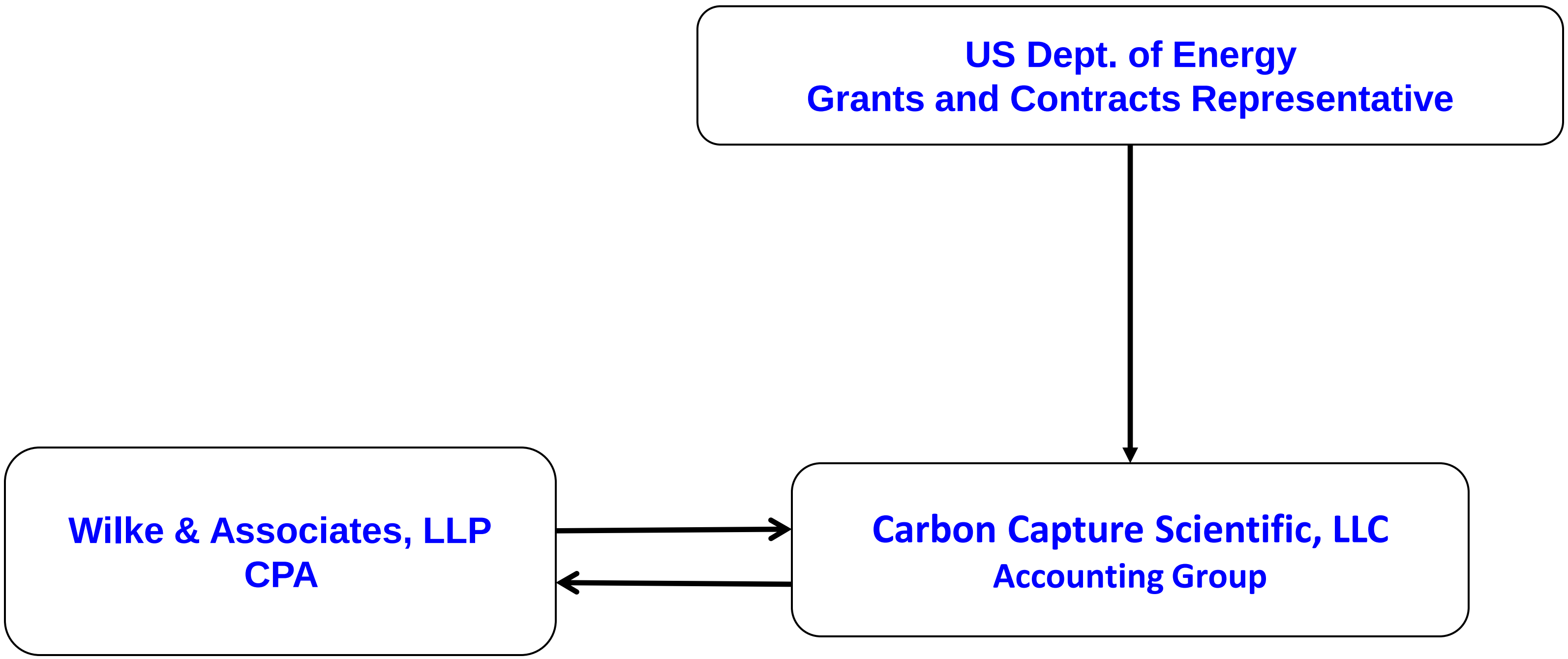
Task 12. Survey of EH&S of GPS process
CCS leads
Dr. Shiaoguo Chen (CCS, 146 hours)
Dr. Zhiwei Li (CCS, 330 hours)

Task 13. Preliminary techno-economic analysis
Nexant leads
Dr. Gerald Choi (Nexant, 140 hours)
Mr. Robert Chu (Nexant, 160 hours)

Task 14. Revision of techno-economic analysis
Nexant leads
Dr. Gerald Choi (Nexant, 50 hours)
Mr. Robert Chu (Nexant, 160 hours)

Task 15. Updated techno-economic analysis
Nexant leads
Dr. Gerald Choi (Nexant, 100 hours)
Mr. Robert Chu (Nexant, 115 hours)

Financial Program Management



Project Schedule: Oct.1, 2011 – Sept.30, 2014

Months after contract award	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Task 1. Project planning & management																																				
1.1 Project planning																																				
1.2 Project management and reporting			Q			Q			Q			Q			Q			Q			Q			Q			Q			Q			Q			F
Task 2. GPS column study and its optimization																																				
2.1 GPS column performance study																																				
2.2 GPS column optimization												A																								
Task 3. Optimization of GPS process for existing plant																																				
3.1 Impact of absorption temperature on energy use																																				
3.2 Impact of steam extraction on LP turbine																								C												
Task 4. Optimization of flashers																																				
4.1 GPS based CO_2 compression																																				
4.2 Liquefaction-based CO_2 compression					BP1																															
Task 5. Phase equilibrium data measurement																																				
5.1 Experimental system set-up																																				
5.2 Data measurement																																				
5.3 Flasher test																BP2																				
Task 6. First absorption column testing																																				
6.1 Design and set-up of column																																				
6.2 Testing of the selected solvents																																				
Task 7. GPS column design/fabrication and testing																														BP3						
7.1 Design and fabrication																																				
7.2 Installation and shakedown																																				
7.3 Testing of the selected solvents																								D												
Task 8. Second absorption column testing																																				
8.1 Modification, installation and shakedown																																				
8.2 Testing for selected solvents																																	E			
Task 9. Stability of solvent at high loading and high T																																				
9.1 Experimental system set up																																				
9.2 Thermal stability test																																				
9.3 Oxidative stability test												B																								
Task 10. Corrosion test at high loading and high T																																				
10.1 experimental system set-up																																				
10.2 Corrosion at high loading																																				
10.3 Corrosion under oxygen																																				
Task 11. Physical properties measurement																																				
11.1 System set-up and C_p measurement																																				
11.2 System set-up and viscosity measurement																																				
Task 12. Survey of EH&S of GPS process																																				
Task 13. Preliminary techno-economic analysis																																				
13.1 Process unit equipment sizing																																				
13.2 Techno-economic analysis																																				
Task 14. Revision of techno-economic analysis																																				
Task 15. Updated techno-economic analysis																																				
15.1 Equipment sizing using updated data																																				
15.2 Techno-economic analysis																																		F			

Project Milestone Log

A	GPS column study and optimization to achieve thermal efficiency of 60% or greater
B	Solvent loss due to degradation of solvent is less than 3 kg/ ton CO_2
C	Overall energy performance column and solvent less than or equal to 0.22 kwh/kg CO_2
D	GPS column efficiency experimental measured at 50% or greater
E	Overall energy performance of system less than or equal to 0.20 kwh/kgCO_2
F	Increase in capital equipment costs of less than or equal to 20% over existing process

Success Criteria / Decision Points / Actions to be Taken

Success Criteria	Decision Point / Actions
Solvent Loss due to degradation < 3 kg/ ton CO_2	Loss due to degradation >3 kg/ ton CO_2 • Lower operating temperatures in the GPS column and flashers • Change solvent concentration
Techno-economics Capital cost of GPS process < 20% increase over conventional amine process	Capital cost of GPS process > 20% increase over those for conventional amine-based processes • Modify operating conditions of some critical units • Example: higher operating pressure for GPS columns and flashers may improve thermodynamic efficiency of the process, but could impact capital cost
Process Energy Consumption (including compression) < 0.22kWh/kgCO_2	Total energy consumption (including compression) > 0.22kWh/kgCO_2, • Review simulation and experimental results • Additional process optimization studies performed to identify and resolve problems

Mitigating Technical Risks

Description of Risk	Probability (L,M,H)	Impact (L,M,H)	Risk Management (Mitigation and Response Strategies)
Technical Risks:			
<u>SOLVENT</u> **Stability Issues**	M	L	1. First, the operating temperature of the flashers will be lowered so that loss will be reduced to an acceptable level 2. Second, if the first step is not enough, the operating temperature of the GPS column will be reduced so that solvent loss will be reduced to an acceptable level 3. Amine stabilization chemicals will be added if possible
<u>SOLVENT</u> **Excessive Corrosion**	L	L	1. Construction materials of the flashers with more resistance to corrosion will be selected. 2. Corrosion inhibitors will be added to the system to prevent the corrosion
<u>SOLVENT</u> **Foaming**	M	L	1. Anti-foaming chemicals will be added to the system
<u>ECONOMICS</u> **Not achieving targets**	L	H	1. Identify the process units which are critical to the process economics 2. Analyze the issues related to the high capital cost
<u>SOLVENT</u> **Environmental, health and safety (EH&S) issues**	L	L	1. Identify the issues and propose mitigation pathways 2. Change solvent formulation 3. Replace with a better solvent

Project Deliverables

- Project Management Plan
- Quarterly progressive reports
- Annual DOE contractors meeting
- Final technical report
  - Summary of all development, analysis, testing, design, and economic analysis
- Other reports
  - Financial, property, annual renewal, and close-out reporting, as defined in contract

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Questions/ Comments?

Minimum Work of CO_2 Capture --- Continued

B. Minimum Work of CO_2 Compression (from 1 atm):

$$W_{\min,comp} = \Delta H - T\Delta S$$

T (C)	P (atm)	H (kJ/mol)	S (J/mol*K)	$W_{min,comp}$ (kJ/mol)	RT ln(P_2/P_1) (kJ/mol)
40	1	22.828	122.3	0	0
40	20	22.066	95.654	7.58	7.80
40	40	21.101	87.59	9.14	9.60
40	80	17.543	72.305	10.37	11.40
40	150	12.543	54.737	10.87	13.04

C. Overall Minimum Work:

$$W_{\min} = W_{\min,sep} + W_{\min,comp} = 8.36 + 10.37 = 18.73 (kJ / molCO_2)$$
$$= 425.7 (kJ / kgCO_2) = 0.118 (kWh / kgCO_2)$$

Minimum Work of CO_2 Capture ---Continued